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A Method for Evaluation of Model-Generated Vertical Profiles of Meteorological Variables

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14. ABSTRACT

Meteorological centers compare global and large-scale regional model output vs. radiosonde data more or less continuously for specific models and also make intermodel comparisons. They normally provide comparisons of meteorological variables at standard pressure levels, and similar comparisons for finer-scale models may be found as output from field tests and other experiments. Additional means to more fully evaluate vertical profiles derived from model output should help provide a more complete evaluation of model output as compared to observations. Here we develop methods to produce vertical profiles of meteorological variables in terms of height and pressure levels, and generate integrated mean value profiles of those variables for layers as defined by user input. These output profiles were entered into spreadsheets for calculation of the derived variables of density and vector wind speed. The level and mean layer values from the Weather Research and Forecasting model (version 3.6.1) were compared to level and layer values from co-incident World Meteorological Organization radiosonde observation data and the differences computed for the several variables. The methods developed here may be used for a variety of model-generated and observed vertical profiles with only minimal changes, primarily to the input function.

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1. Introduction

Vertical profiles of meteorological variables produced by numerical weather prediction (NWP) models can be compared to data from World Meteorological Organization (WMO) and other radiosondes. Other sources of comparison data may come from, for example, radar profilers and lidar for wind, microwave radiometers for temperature and moisture parameters, and radio acoustic sounding systems (RASSs) for virtual temperature. Nevertheless, radiosondes have remained the primary source of comparison data above the near surface layer, starting roughly tens of meters to perhaps 100 m above the surface.

Meteorological centers compare global and large-scale regional model output vs. radiosonde data more or less continuously and make intermodel comparisons. The National Center for Environmental Prediction (NCEP) has a readily accessible website (http://www.emc.ncep.noaa.gov/gmb/STATS_vsdb/) and the European Center for Medium-Range Weather Forecasting (ECMWF) provides related information on their website (http://www.ecmwf.int/en/forecasts/charts/medium/monthly-wmo-scores-against-radiosondes). Worldwide comparisons are available for deterministic forecasts at the ECMWF (http://apps.ecmwf.int/wmolcdnv/) and ensemble forecasts at the Japan Meteorological Agency (JMA) (http://epsv.kishou.go.jp/EPSv/). They provide comparisons of meteorological variables at the standard WMO pressure levels (e.g., 850, 700, 500, 400 hPa).

Some documentation with respect to these comparisons and model details may be found via the respective web pages. For the ECMWF, one can go to http://www.ecmwf.int/search/elibrary/. For the NCEP, the following page and included links lead to various documents and other information on models and related datasets: http://www.emc.ncep.noaa.gov/?doc=doc.

Somewhat similar comparisons of radiosondes and smaller-scale models may be found in the published literature. Schroeder et al. (2006) investigated most of the vertical extent of the Meteorological Model Fifth Generation (MM5) and presented results for standard pressure levels from 850 to 100 hPa (some graphs to 150 hPa) in their evaluation of their automated rapidly relocatable nowcasting and prediction system. They worked with data for 8 days in April 2002, 12 days in the winter and summer of 2003, and 18 days in August 2001. The former 2 periods were from the East Coast region of the United States and the latter from the Great Plains region of the United States. Cuevas et al. (2011) made 21 Weather Research and Forecasting (WRF) to radiosonde comparisons in Chile during 24 October–4 November 2011. While the emphasis in the report concerned precipitable water vapor (PWV) forecasts for use by the Southern European Observatory, it presented

vertical profiles of the mean, bias, and root mean squared error (RMSE) of several other meteorological variables such as temperature, humidity, and wind speed that were compared as a function of pressure level. Cortes and Cure (2011) compared results from the Global Forecast System (GFS), the ECMWF model, and WRF at the standard pressure levels for locations in northern Chile. Kilpelainen et al. (2012) and Dutsch (2012) each evaluated WRF output for the boundary layer over Svalbard in the Arctic in terms of height above ground compared to tower and tethered balloon (tethersonde) data and radiosonde data, respectively. The tethersondes provided data from the surface up to about 600, 800, and 1250 m for each of 3 sites. The radiosonde data reached as high as 2 km above the surface. Additionally, Behne (2008) addressed wind speed as derived from wind components (vector wind speed/magnitude).

Other means to more fully evaluate vertical profiles derived from model output should help in the evaluation of model output as compared to observations, for example, as compared to data from radiosondes or for wind to data from radar profilers or lidars. Here we develop methods to produce vertical profiles of meteorological variables in terms of height and pressure levels, and generate integrated mean value profiles of those variables for layers as defined by the user-input values of boundary heights or pressures. The output profiles are entered into spreadsheets for calculation of the derived variables of density and vector wind speed or vector wind magnitude where those latter terms refer to wind speed derived from the u and v wind components.

The level and mean layer values from WRF (version 3.6.1) are compared to values from co-incident WMO radiosonde observation (RAOB) data and the differences computed for the several variables. Skamarock et al. (2008) describe the basics of the WRF model, though there have been some changes in the more recent versions. In addition statistical values are produced for each level or layer. Though the set of data is not large enough to be definitive with respect to WRF accuracy, the statistics appear reasonable, and the values for model output pressure levels or equivalent heights are generally in line with previously published values as well as with values for pressure levels from global models at the operational sites noted above. Here accuracy is defined as the closeness to values from co-incident radiosondes. The methods developed here may be used for a variety of model generated and observed vertical profiles with only minimal changes, primarily to the function that reads the input data.

2. Method

The generation of the 4 types of output described in this report is based on the algorithms and software described in Cogan (2015). Here we describe the height- and pressure-based methods; for each type, there is one method for values at user selected levels and one for the layers defined by those levels. The selected heights or pressure levels are entered via a user-generated parameter file. It contains a list of the desired heights or pressures starting from the lowest height in terms of above ground level (AGL) or the highest pressure, respectively, normally values for the surface. The 4 types of vertical profiles are height level, height layer, pressure level, and pressure layer. These methods were used to produce RAOB- and WRF-based profile comparisons for 2 times for each of 15 WMO radiosonde sites in the Southwest United States, Mid-Atlantic United States, Germany, and South Korea for a total of 30 comparisons.

2.1 RAOB Soundings and WRF Output for Profile Generation

The RAOB data were obtained from the University of Wyoming's weather website (http://www.weather.uwyo.edu/upperair/sounding.html). That site contains WMO soundings in several formats including text as used here. Other sites are available that have WMO sounding data but require different processing in the input function (e.g., http://www.esrl.noaa.gov/raobs). The sounding data are transferred to text files for input to the program as in Cogan (2015). As in the earlier program, the data are entered into a "standard" array for further processing. One input function is used for all of the methods for radiosonde sounding data, and a second input function for all of those for model output profiles.

WRF v3.6.1 was run with 9/3/1 km horizontal grid spacing nested domains. The 30 comparisons for this report used data from the 3-km domain. The initial and boundary conditions were derived from GFS 0.5° horizontal grid spacing with a 3-h time interval. Where available, GFS snow fields were replaced with 1) 1-km snow fields from the National Weather Service's National Operational Hydrologic Remote Sensing Center (NOHRSC) (http://www.nohrsc.noaa.gov/technology/) Snow Data Assimilation System (SNODAS), or if 1) was not available with 2) 4-km snow cover fields from the National Ice Center's Interactive Multi-sensor Snow and Ice Mapping System (IMS) (http://nsidc.org/data/docs/noaa/g02156_ims_snow_ice_analysis/). Consequently, when available, NOHRSC fields were used for an area centered on the United States, IMS data for the rest of the northern hemisphere, and GFS fields for the southern hemisphere.

A sea surface temperature product with higher resolution than the GFS output is produced by the NCEP Prediction, Marine Modeling and Analysis Branch, called the Real Time Global Sea Surface Temperature (Gemmill et al. 2007), which has 1/12th-degree horizontal grid spacing and was used to specify sea surface temperatures. Observation "nudging" data assimilation ingested observations during a 3.5-h preforecast period. Above-surface observations are used in assimilation if they are within 1.5 h of the current time, while the time window for surface observations is 75% as long (67.5 min). It nudged the model toward observations of temperature, moisture, and wind; these observations when available include Meteorological Assimilation Data Ingest System (MADIS) data from radiosondes, Meteorological Aerodrome Report (METAR), Surface Aviation Observation (SAO, mostly from Canada), and maritime (e.g., ship) observations. These observations are only entered if they pass the quality control procedures and are within the respective time window. The Mellor-Yamada-Janjić scheme (MYJ) is used to parameterize the atmospheric boundary layer. As in Lee et al. (2012) and Reen et al. (2014), the background turbulent kinetic energy is decreased to better simulate conditions with low turbulent kinetic energy and the atmospheric boundary layer depth diagnosis is altered. The WRF single-moment 5-class microphysics parameterization and the Kain-Fritsch cumulus parameterization (9-km domain only) are used. For radiation, the Rapid Radiative Transfer Model is used for longwave and the Dudhia scheme for shortwave. The Noah land surface model is used to represent land surface processes. The pre-processing software included updates by Reen (2015).

WRF was run for 21 model hours starting 3 h after either 00 UTC or 12 UTC with data extracted from the 9-h files leading to output for 12 UTC or 00 UTC the next day, respectively. The model time of 9 h was chosen so that the output could serve additional investigations beyond the scope of this study. The profiles of meteorological variables were then extracted from the WRF NetCDF output files via a National Center for Atmospheric Research (NCAR) Command Language (NCL) script and placed into text files that included a header with information on the location, time, model grid resolution, and the method (if any) employed to interpolate between model grid points to the selected location (Reen 2015). These profiles contain data lines for heights above mean sea level (MSL) of pressure levels. The user has the option to use a "sounding" from the nearest grid point (i.e., no interpolation), or either bilinear interpolation or inverse distance weight interpolation (via built-in NCL capabilities).

2.2 Height-Based Profiles

The software for height-based output required minimal modification to the program described in Cogan (2015) including changes to produce height output at specific heights as well as layer output. This revised version also is written in the "C" language and that language's terminology is used herein, such as the term function for a sub-program or routine. Appendix A contains details on the changes to the earlier software, but does not repeat the entire program.

The changes to the earlier software mostly involved the addition of output at the user-defined heights. Those values were computed previously as part of the calculation of the mean layer values, but were not included in the output. The present version has an additional function that produces height level output. As before, the user defines the output height profile in a parameter file and that, in turn, defines the upper and lower boundaries of the computed integrated mean layer values (a.k.a. weighted mean values). For both the level and layer output, the initial data line contains the input profile's surface values, but converted to the output format. Subsequent data lines denote either level or layer output, respectively. For the level output, the values displayed are those computed for the listed heights. The layer "height" displayed is the midpoint height of the layer, but a given data value may not represent the exact value at the midpoint height since it is the weighted mean of that layer. The exception is pressure, which is calculated for the midpoint using the hypsometric formula starting from the closest data level immediately below or the lower boundary value if there is no data level between the lower boundary height and the midpoint.

The input list of heights in the parameter file may be modified by the user as long as there are 2 levels, a "surface" (at the surface or defined lowest level) and top level. Heights are listed as AGL. With minimal modification the program will list heights as above MSL in the output. The user-input levels may define a vertical spacing or interval between heights or layer thickness from a fraction of meter to the entire vertical extent that can exceed several kilometers. However, the user should be aware of the vertical spacing between input data levels of the RAOB or extracted WRF profiles before using a very small or large interval.

2.3 Pressure-Based Profiles

The methods presented in this section also are based on those presented in Cogan (2015) but required more extensive modification than for height-based output. Appendix A contains details on these changes but, as with the height-based versions, does not repeat the entire program. Earlier and ongoing efforts as

referenced in the introduction provide comparisons for standard pressure levels or model output pressure levels for specified periods during field tests. The methods derived herein are not limited to either standard or model output levels. As with the height-based methods, the user defines the vertical levels, in this case, pressure instead of height.

The software produces profiles of the several variables for pressure levels or layers specified via the user's parameter file. The "surface" values for either the level or layer output repeat the input surface values, and that input is used to compute the derived surface variables (e.g., density), with appropriate changes in units. The user may specify pressure levels that produce intervals that range from a fraction of a hectopascal to the entire vertical extent, but the user has to include at least a lowest pressure level (highest pressure) and the top pressure level (lowest pressure). However, as a general rule the pressure level intervals should not be too large (e.g., not greater than about 50 hPa) and consider the altitude since a change of, say, 25 hPa, is not too large near the surface, but may be near the 50 hPa level. Also, the input pressure intervals should be considered since a very fine output interval (e.g., 1 hPa or less) may not yield much additional information if the input interval is much larger (e.g., 25 hPa).

Modifications to the software to enable pressure-based output included changes to the output functions and modification of the function that produces the level and layer values. The standard version of the program linearly interpolates all variables (e.g., height, temperature) in terms of the natural log of pressure, ln(P). An alternative version of the program computes height for a user-defined level using the hypsometric formula from the input pressure level immediately below (next highest input pressure); this alternative version retains linear in ln(P) interpolation for all other variables. If no data level lies between the given data level and the output data level immediately below, then the program uses the value of pressure at that previous output level. The same procedure applies to computation of the layer value of height except that the hypsometric formula is applied to the midpoint of the data layer (Fig. 1). Figure 2 illustrates the computation of height using linear interpolation in ln(P).

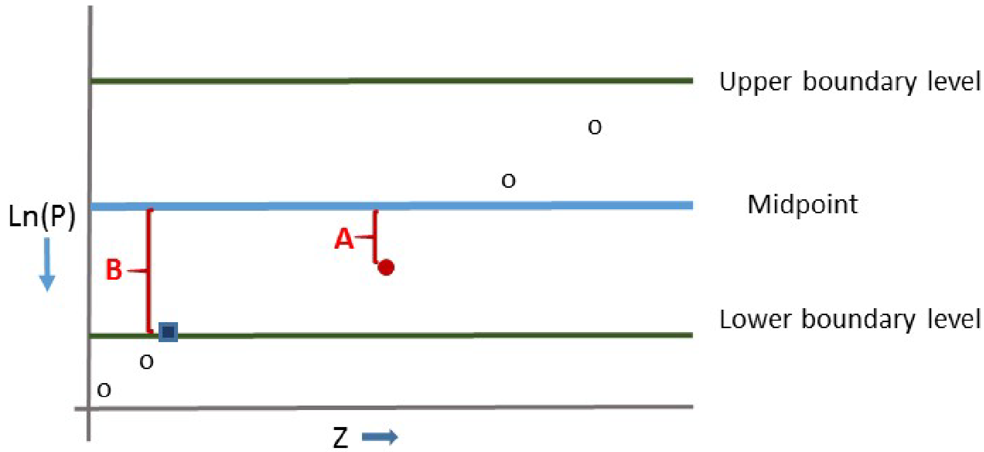

Fig. 1 **Schematic chart based on a similar diagram in Cogan (2015) illustrating the ln(P) level from which the height, Z, of the midpoint is computed using the hypsometric equation. "A" represents computation starting at the data point immediately below the midpoint (solid circle), and "B" indicates computation starting at the lower boundary level (solid square) of a given layer (only undertaken if the point used in "A" is not present).**

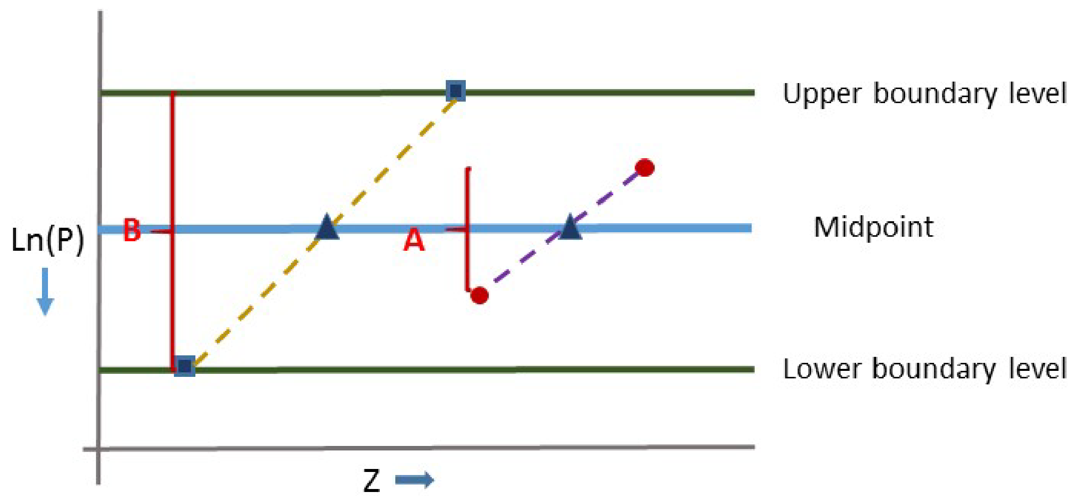

Fig. 2 **Schematic chart illustrating the linear interpolation of height in terms of ln(P) for 2 cases where the solid triangles represent the interpolated values. The first (A) is an example of interpolation between 2 data points that lie within the layer (solid circles). The second (B) is an example of interpolation between boundary levels (solid squares) where there are no data levels within the layer. Intermediate cases can occur where a data level is within the layer above or below the midpoint.**

Several comparisons of the 2 methods for height showed that the output differences in height of pressure levels were small (absolute difference of 0 to 3 m for most RAOB levels to the nearest meter, and 0 to 2 m for WRF levels). The differences in the layer values were somewhat larger, especially for RAOB pressures less than

40 hPa. Standard WRF procedure allows interpolation in either linear or linear in natural log of pressure (via option interp_type as noted in http://www2.mmm.ucar.edu/wrf/users/docs/user_guide_V3/users_guide_chap5.htm). The primary temperature variable in WRF is potential temperature and WRF interpolates it in terms of ln(P) even if the user selects linear in P for the other variables.

The procedure for computation of pressure layer values closely resembles that for computation of height layer values. The main difference is that the vertical coordinate is ln(P) instead of height (Z). Figure 3 illustrates the method for either Z or ln(P) for any of the variables, except for P in the height-based computations where the hypsometric formula is used to compute P as well as Z in the alternate pressure method that also uses the hypsometric formula.

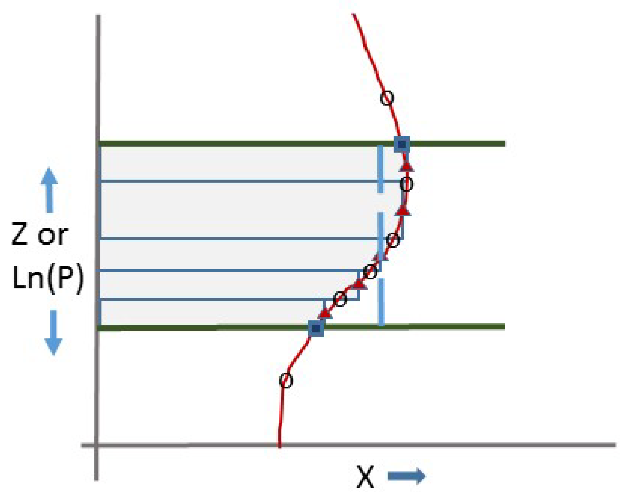

Fig. 3 Schematic based on a similar diagram in Cogan (2015) illustrating the computation of an integrated or weighted mean of some variable X for a layer defined by height (Z), upward arrow, or the natural log of pressure, ln(P), downward arrow. The blue lines represent sublayers with sublayer means indicated by red triangles. Circles indicate the observations or WRF output values and blue squares the values at the upper and lower layer boundary levels.

3. Comparisons

For each method, the data for each pair of RAOB and WRF computed level and each pair of layer profile text files were entered into separate spreadsheets in the form of tables by variable and level or layer. Table 1 provides an example of computed height level values from the 00 UTC RAOB from Wallops Island, Virginia, on 27 October 2015, which has the same format as the co-incident data from WRF. The heights are in meters above ground level (m AGL). Only the first 12 of 60 levels are shown.

Table 1 Sample of height level "sounding" derived from RAOB data at 00 UTC on 27 October 2015 at Wallops Island, Virginia. Height is in m AGL, wind direction (W dir) in degrees, wind speed (W spd) in knots, virtual temperature (T_v) and sensible temperature (T) in K, and pressure (P) in hPa.

Level	Height	W dir	W spd	T_v	P	T
0	0	350	6.0	285.7	1029.0	284.6
1	50	6	7.2	285.5	1022.9	284.5
2	100	16	8.7	285.4	1016.8	284.4
3	200	38	11.8	284.9	1004.3	284.0
4	300	50	16.0	284.1	992.1	283.2
5	400	54	16.3	283.2	980.2	282.3
6	500	57	16.6	282.2	968.4	281.4
7	600	60	17.0	281.3	956.6	280.4
8	700	64	16.6	280.4	945.0	279.5
9	800	67	16.2	279.5	933.5	278.6
10	900	70	16.0	278.6	922.4	277.8
11	1000	63	16.0	278.1	911.1	277.4

Table 2 presents a similar example, but for computed pressure level values from the 00 UTC RAOB, also from Wallops Island on 27 October 2015. The co-incident WRF "sounding" has the same format and pressure levels. The pressure values shown are those listed in the user-provided parameter file and almost always are above the surface. An exception could occur if both the WRF and RAOB profiles had the same surface pressure and that was the same as a value in the parameter file.

Table 2 Sample of pressure level "sounding" derived from RAOB data. Pressure (P) is in hPa, height in m AGL, wind direction (W dir) in degrees, wind speed (W spd) in knots, and virtual temperature (T_v) and sensible temperature (T) in K. Data for Wallops Island, Virginia, on 27 October 2015 at 00 UTC.

Level	P	Height	W dir	W spd	T_v	T
0	1020	72	11	7.8	285.5	284.5
1	1010	152	27	10.4	285.2	284.3
2	1000	234	45	13.0	284.7	283.8
3	990	317	51	16.1	283.9	283.0
4	975	443	55	16.4	282.8	281.9
5	950	657	62	16.7	280.8	279.9
6	925	877	70	16.0	278.8	278.0
7	900	1100	57	16.0	280.5	280.4
8	875	1332	52	14.5	281.4	281.4
9	850	1571	55	11.0	280.6	280.6
10	825	1815	50	11.0	279.8	279.8
11	800	2067	1	5.1	279.0	279.0

The differences between the WRF and RAOB values are listed in a table on the same spreadsheet by each variable and level or layer. In addition to the aforementioned variables, spreadsheet functions compute density (Den) difference, in gm^{-3} and vector wind magnitude (V-W) difference, in knots. The difference

values for each variable is written to a summary spreadsheet for each of the levels or layers. The summary sheet is set up so that standard statistics, i.e., mean value (M), mean absolute error (MAE), standard deviation (SD), and RMSE, are computed for each level or layer for each variable. For this set of comparisons "error" really refers to difference, and from here on, this report uses the terms mean difference (MD), mean absolute difference (MAD), SD of the differences, and root mean square difference (RMSD). Table 3 presents a sample of the height-based difference output for the same set of profiles, that is, for Wallops Island on 27 October 2015 at 00 UTC. Some intermediate values have been omitted such as the outcomes of modifying the wind direction by adding 360° to one of the profiles if the absolute value of the initial direction difference would exceed 180° (e.g., if WRF value – RAOB value = |10 – 350| = 340°, add 360 to the WRF value: 10+360 – 350 = 20° difference). Only the first 12 of 60 levels are shown.

Table 3 Sample of differences in listed variables derived from WRF and RAOB data (WRF – RAOB) for listed height (m AGL) levels. Difference is in wind direction (W dir) is in degrees, wind speed (W spd) in knots, virtual temperature (T_v) and sensible temperature (T) in K, pressure (P) in hPa, density (Den) in gm^{-3}, and vector wind magnitude (V-W) in knots. Data for Wallops Island, Virginia, on 27 October 2015 at 00 UTC.

Level	Height	W dir	W spd	T_v	T	P	Den	V-W
0	0	55	6.3	1.1	1.1	0.7	–3.96	10.13
1	50	41	8.0	1.6	1.4	0.5	–6.35	10.85
2	100	33	8.8	1.4	1.2	0.6	–5.33	11.25
3	200	13	7.3	1.0	0.8	1.0	–3.08	8.05
4	300	2	3.7	0.8	0.6	1.2	–1.95	3.75
5	400	–1	3.6	0.7	0.5	1.2	–1.50	3.61
6	500	–4	3.4	0.7	0.4	1.3	–1.36	3.63
7	600	–6	3.1	0.6	0.5	1.4	–0.79	3.65
8	700	–10	3.2	0.6	0.5	1.5	–0.65	4.50
9	800	–9	2.1	1.0	1.3	1.5	–2.29	3.42
10	900	–12	–0.1	2.3	2.8	1.3	–7.83	3.34
11	1000	–5	–2.0	3.3	3.9	1.4	–11.65	2.39

A similar table of difference values was computed for the pressure level–based data, but with a column for height differences vs. pressure differences. The same types of tables were computed for the layer output. However, for the height-based data, the listed heights were the layer midpoints. For the pressure-based data, the listed pressures were the averages of the upper and lower boundary pressures. Table 4 presents difference data from Kwangju, South Korea, for 15 September 2015 at 12 UTC for the surface and first 6 of 59 height layers. Level 0 contains the surface data with format changes and variables derived from those data (e.g., density). The layer 0 data line has the same values as the height level 0 line. Layers starting at 1 contain layer values.

Table 4 Difference data as in Table 3 (WRF – RAOB), but for the surface and first 6 height layers. The variables have the same units as in Table 3. The listed heights except for the surface (layer 0) are the midpoints of the respective layers. Data for Kwangju, South Korea, for 15 September 2015 at 12 UTC.

Layer	Height	W dir	W spd	T_v	T	P	Den	V-W
0	0	52	4.0	–3.9	–3.9	1.2	17.27	4.00
1	25	–20	4.3	–2.6	–2.5	1.1	11.80	4.35
2	75	–2	5.7	–1.3	–1.3	1.0	6.38	5.70
3	150	3	5.7	–1.3	–1.3	0.6	5.88	5.71
4	250	–7	4.9	–1.3	–1.5	0.6	5.85	5.03
5	350	–13	3.3	–1.4	–1.6	0.6	6.22	4.19
6	450	–16	1.8	–1.5	–1.7	0.5	6.47	4.23

Table 5 presents difference data from Kwangju, South Korea, for 15 September 2015 at 12 UTC for the first 6 of 62 pressure layers. For pressure-based data, if the highest pressures for the WRF- and RAOB-based profiles are above the specified pressure of the lower boundary of the initial user-defined layer then the output will include that layer (layer 0). Otherwise, the first user layer to be output is the one immediately above (i.e., layer 1) and so on for subsequent layers. In the example shown, the highest pressure for the WRF as well as RAOB profiles were less than the 1020 hPa specified for the lower boundary of layer 0 and therefore no 1015 hPa layer difference values were computed.

Table 5 Difference data (WRF – RAOB) as in Table 4, but for the first 6 pressure layers. The variables have the same units as in Table 4. The listed pressures are the "midpoints" (average of boundary pressures) of the respective layers. Data for Kwangju, South Korea, for 15 September 2015 at 12 UTC.

Layer	Press	W dir	W spd	T_v	T	P	Den	V-W
1	1005.0	3	5.9	–1.3	–1.3	7.0	5.20	5.91
2	995.0	0	5.7	–1.4	–1.4	6.0	5.56	5.70
3	982.5	–9	4.4	–1.4	–1.6	6.0	5.53	4.68
4	962.5	–15	2.6	–1.5	–1.8	6.0	5.86	4.41
5	937.5	–4	6.9	–1.4	–1.7	4.0	5.40	6.95
6	912.5	13	6.5	–1.0	–1.3	3.0	3.80	6.93

Several standard statistical measures were computed for each of the 4 methods for each variable (direct or derived) for all of the individual levels or layers covering all 30 radiosondes used for comparison against WRF model output. As noted above the measures were MD, MAD, SD, and RMSD. Tables of the statistical values were generated and entered into tables on a spreadsheet, which, in turn, were used to produce graphical representations. Figures 4–7 present those 4 statistics for height levels and layers and pressure levels and layers for temperature and vector wind magnitude. The vector wind magnitude is always positive, hence the MD and MAD values are the same. On the scale of the charts, SD and RMSD frequently overlap.

The complete set of charts for the height and pressure levels and layers measures for all variables are presented in Appendix B.

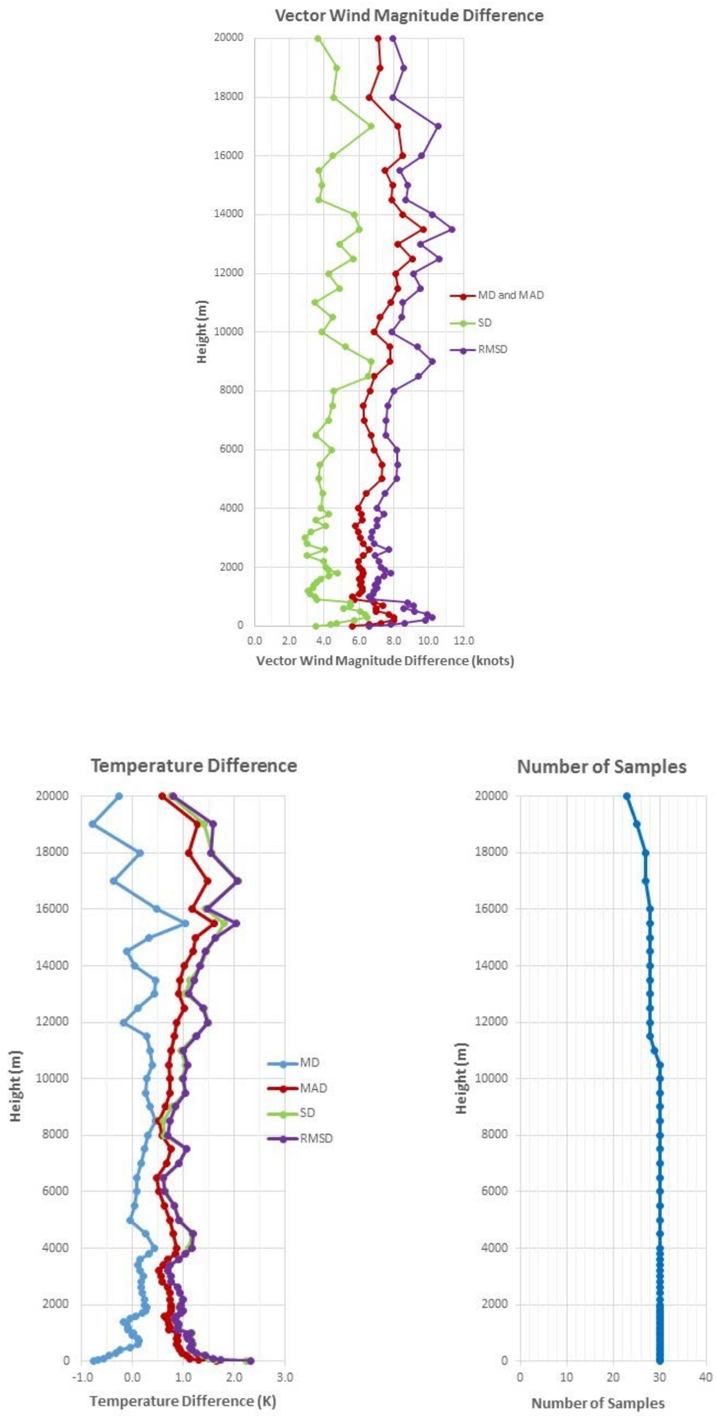

Fig. 4 Statistical values (MD, MAD, SD, and RMSD) for vector wind magnitude and temperature for the user-defined height levels along with the number of samples for each level

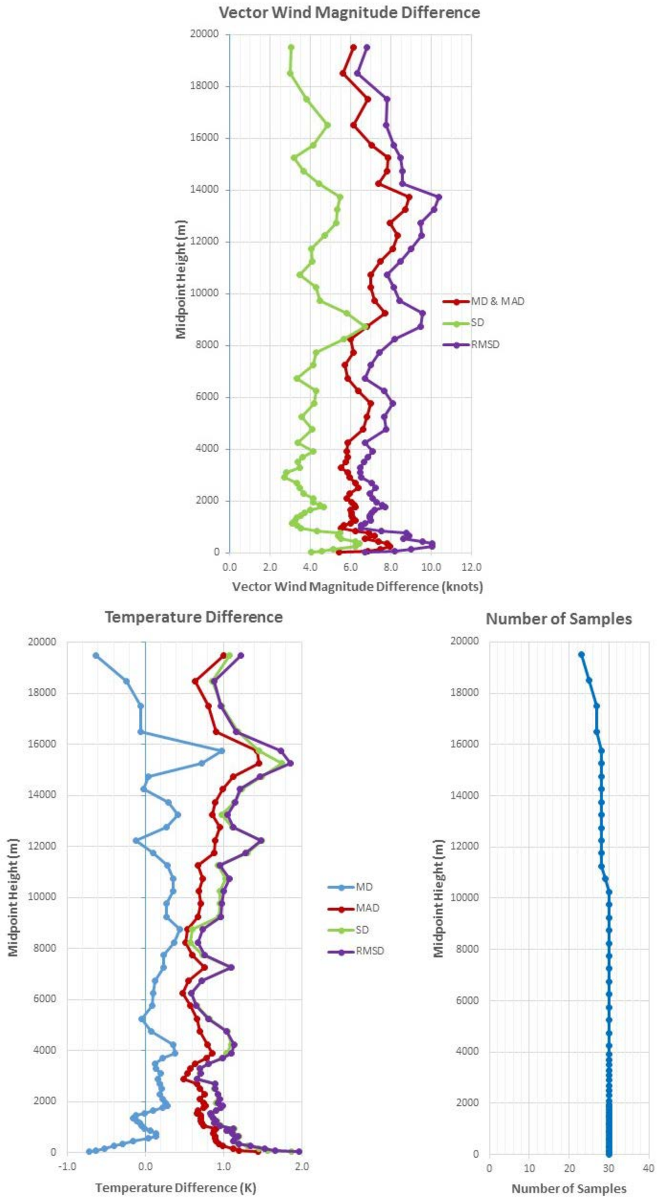

Fig. 5 Statistical values (MD, MAD, SD, and RMSD) for vector wind magnitude and temperature for height layers defined by the user input height levels along with the number of samples for each layer

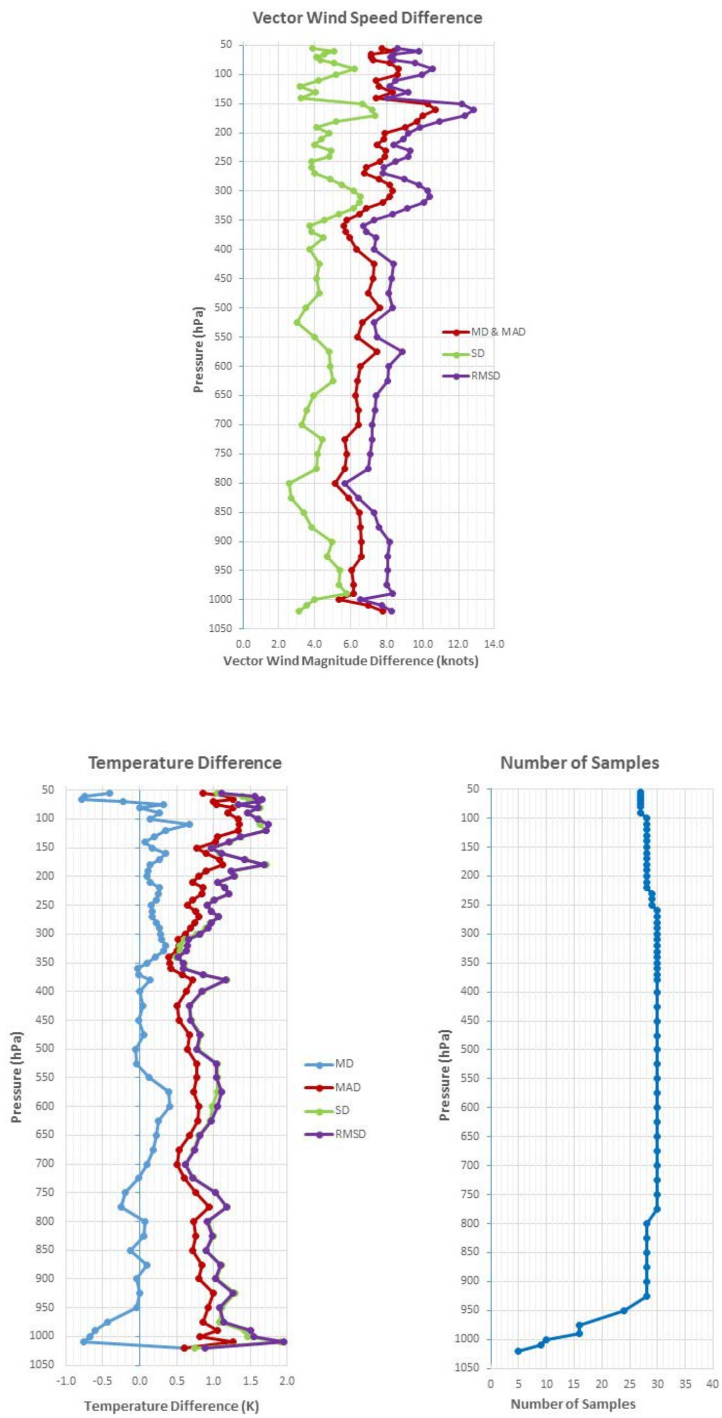

Fig. 6 Statistical values (MD, MAD, SD, and RMSD) for vector wind magnitude and temperature for pressure levels defined by the user along with the number of samples for each level

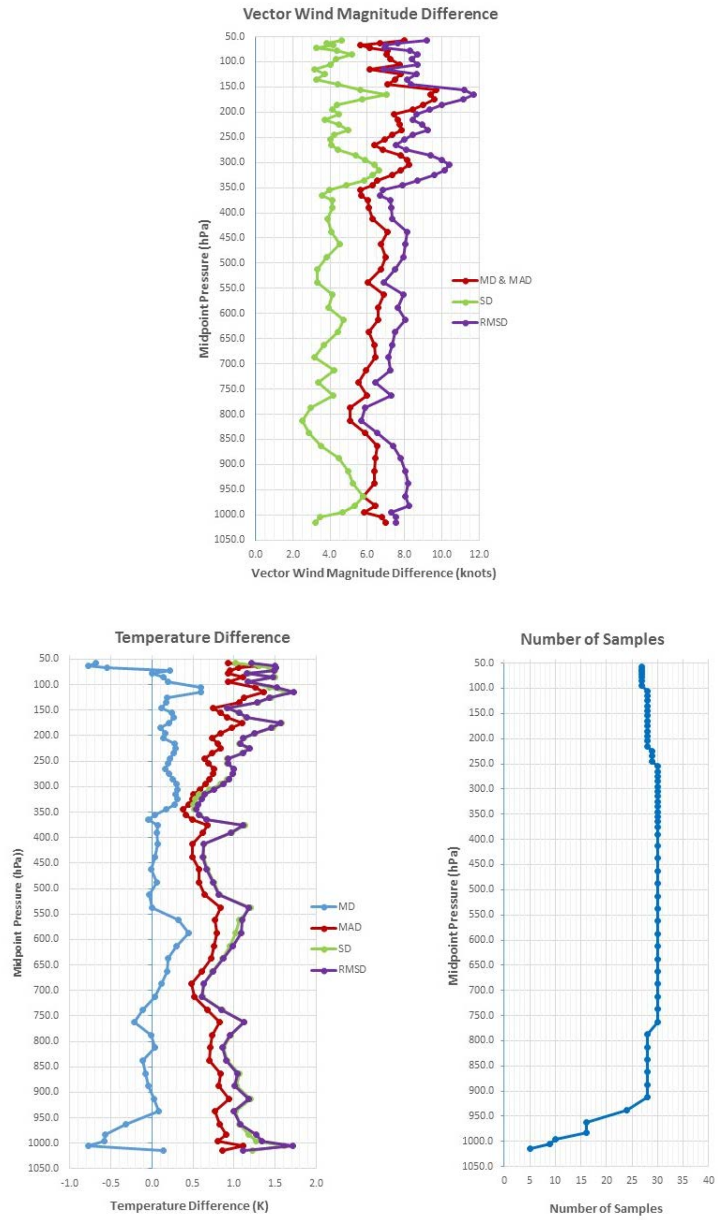

Fig. 7 Statistical values (MD, MAD, SD, and RMSD) for vector wind magnitude and temperature for pressure layers defined by the user-defined levels along with the number of samples for each layer

Earlier published and ongoing comparisons at operational centers as noted in the references and websites in Section 1 provide values of some meteorological variables between model output and radiosonde soundings for several standard pressure levels and some limited comparisons for model output pressure levels and equivalent heights. Converting the wind units here from knots to meter per second (m s^{-1}) shows that the results here are roughly comparable with respect to wind. That also holds for the other directly measured meteorological variables. The

computed values of height for the compared standard levels (850, 500, 250 hPa) on the ECMWF website for deterministic output at 24 h of model time for the northern hemisphere from several national models had noticeably lower values for 850 and 250 hPa and somewhat lower at 500 hPa.

The initialization model for this study, GFS, has an accuracy close to or about equal to that for the other models based on the data presented on the ECMWF site (excluding an outlier that showed greater differences). However, the locations examined for this report included some in or very near complex terrain. The profile data for the 2 sites with the largest height differences, Kwangju, Korea, and Blacksburg, Virginia, had the WRF surface height significantly different from that of the radiosonde launch site, about 35–38 m lower. The respective pressure differences were about 6 and 2 hPa higher. With those removed the computed heights were closer, with the 500 hPa value slightly better than the ECMWF mean value, the value for 850 hPa was slightly higher than the mean of the models, and the 250 hPa value was within the spread of the several models displayed. The discrepancies with respect to surface height and pressure suggests that finer-scale versions of WRF (e.g., 1 or 0.5 km) could help if the terrain data base also has a finer grid resolution than as used in this study. However, that remains to be determined.

4. Summary and Conclusion

Two methods were developed to provide vertical profiles of meteorological variables and some derived quantities from radiosonde and model output at user-specified height or pressure levels. Two other methods provide profiles of integrated or weighted mean values for layers based on those user-specified levels. Ongoing comparisons at data centers have concentrated on comparing models and some of those models with radiosonde data at standard pressure levels plus surface values. Limited comparisons elsewhere for soundings derived from model output for data levels at model computed pressure levels, or equivalent heights (often within or not far above the boundary layer), have occurred for relatively short experimental periods at specific sites.

The emphasis at operational data centers tends toward wind speed, temperature, and geopotential height, though other variables are addressed such as relative humidity. The methods developed here can produce output that is not limited to standard pressure levels or model output pressure levels (or equivalent heights). Furthermore, these methods may be applied to applications other than model comparisons with radiosonde data such as inter-comparison of observation systems such as radar wind profilers with lidars, comparisons of different model configurations, and determination of the best types of vertical profiles for specific applications.

The use of pressure-level data over varying terrain may cause some confusion since for a given level some locations may be close to the surface while others are not. For example, a common surface pressure at Flagstaff, Arizona (2192 m above mean sea level), may range from 780 to 790 hPa. Comparing data from, say Phoenix, Arizona (384 m above mean sea level), with those from Flagstaff for the 850 hPa pressure level does not have much value. However, looking at data for a comparison at a height of, say, 500 m AGL could have some use for a boundary layer investigation. This "discrepancy" between common practice and potential needs suggests a hybrid vertical profile to compare model output with observations above the surface. This procedure would use a vertical profile based on height AGL for the lower part of a hybrid profile, for example, from the surface to perhaps the lowest hundreds of meters to a few km above the surface, and a vertical profile based on pressure level above. The same could apply to vertical layer profiles.

The use of vertical profiles of atmospheric layers provides a means to sample the atmosphere in a semi-continuous fashion vs. a series of point values upward from the surface. The layers can be very thin for close examination and allowed to be thicker for regions of less detailed study. One could select layers only 10, 5, or even 1 m thick near the top of the boundary layer and perhaps 500 m thick in the upper troposphere before approaching the tropopause where perhaps 50-m layers could be useful. If pressure-level layers were preferred then perhaps 1 to 50 hPa layers could be appropriate, depending on the atmospheric situation. The user can adjust the vertical resolution of the output profiles via modification of a single parameter file, no recompilation or other adjustment is required.

These methods were applied to a set of co-located WRF generated profiles and WMO radiosonde soundings. They provided a sample of the use of the 4 methods for comparing profiles from WRF model output with those from RAOBs for height levels and layers and pressure levels and layers. Several common statistical measures were computed from the resultant difference data. Though somewhat varied in elevation, climate region, etc., the 30 cases of this study can only suggest the potential accuracy of WRF output relative to RAOBs since they are too few for a definitive conclusion in that regard. Here accuracy refers to closeness to the radiosonde observations, and furthermore, a RAOB is only a good estimate of atmospheric conditions due to spatial and temporal drift and instrument errors. Nevertheless, the statistics for standard pressure levels may be compared with those from published site-specific results or displayed on public websites run by meteorological centers, as well as with published site-specific results for model output pressure levels or equivalent heights. Overall the results from this study are in line with the values presented in those references and websites.

5. References

Behne DN. NAM-WRF verification of subtropical jet and turbulence. Electronic Journal of Operational Meteorology, National Weather Association; 2008.

Cogan J. A generalized method for vertical profiles of mean layer values of meteorological variables. Adelphi (MD): Army Research Laboratory (US); 2015. Report No.: ARL-TR-7434.

Cortes L, Cure M. Validation of the vertical profiles of three meteorological models using radiosondes from Antofagasta, Paranal and Llano de Chajnantor. RevMex AA (Serie de Conferencias). 2011;41:640–67.

Cuevas O, Chacon A, Cure M. Radiosonde campaign in Paranal Observatory 2011: PWV measurement. AstroMeteorology group, Physics and Astronomy Dep't, Universidad de Valparaiso, Chile; 2011.

Dutsch ML. Evaluation of the WRF model based on observations made by controlled meteorological balloons in the atmospheric boundary layer of Svalbard. Bergen (Norway): Meteorologisk Institutt; 2012. Technical report.

Gemmill W, Katz B, Li X. Daily real-time, global sea surface temperature–high resolution analysis: RTG_SST_HR. NCEP/EMC Office note, 2007 [accessed DATE]. http://polar.ncep.noaa.gov/mmab/papers/on260/sst_office_note.pdf.

Glickman TS, managing editor. Glossary of meteorology. 2nd ed. Boston (MA): American Meteorological Society; 2000.

Kilpelainen T, Vihma T, Mannienen M, Sjoblom A, Jakobson E, Palo T, Maturilli M. Modelling the vertical structure of the atmospheric boundary layer over Arctic fjords in Svalbard. Q J R Meteorol Soc. 2012;138:1867–1883.

Lee JA, Kolczynski WC, McCandless TC, Haupt SE. An objective methodology for configuring and down-selecting an NWP ensemble for low-level wind prediction. Mon Wea Rev. 2012;140:2270–2286.

Reen B. Affiliation, city, state. Private Communication, 2015.

Reen BP, Stauffer DR, Davis KJ. Land-surface heterogeneity effects in the planetary boundary layer. Boundary-Layer Meteorology. 2014;150:1–31.

Schroeder AJ, Stauffer DR, Seaman NL, Deng A, Gibbs AM, Hunter GK, Young GS. An automated high-resolution, rapidly relocatable meteorological nowcasting and prediction system. Mon Wea Rev. 2006;134:1237-1265.

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barke, DM, Duda MG, Huang X-Y, Wang W, Powers JG. A description of the advanced research WRF. Ver. 3. Boulder (CO): National Center for Atmospheric Sciences; 2008. NCAR Tech. Note NCAR/TN-475+STR.

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Appendix A. Program Modification Descriptions

This appendix contains short summaries in text and pseudo code, if applicable, of the changed sections of the relevant functions in the programs for generation of vertical profiles of meteorological variables for user-defined heights, pressure levels, height layers, and pressure layers. The changes to the height based methods were relatively small since the generation of the output profiles was essentially the same as in Cogan.[1] There were output format changes and other very minor modifications aside from the modification to the parameter file that contained user-defined heights. Changes to the pressure-based methods were more extensive, but not too large. The output function required some modification and the parameter file contains user-defined pressure levels versus heights. A more extensive modification concerned the computation of pressure level and layer values of the variables as well as the calculation of height level and layer values versus pressure values.

A-1 Height-Based Methods

The main changes were modifications to the output function for layer data and a new function for output of level data, plus changes in format. For example temperature and virtual temperature were changed from K*10 to K. Pressure is now labeled in hectopascal (hPa) instead of millibar (mb) to comply with current common usage in the meteorological community. The main computation function, "msgvalues", was essentially unchanged from that described in Cogan.[1] Since the earlier program calculated values of the variables for height levels as part of the computation of layer values for the several types of MET messages, the main change was to retain the arrays of level values for later output. A separate output function was created for the level output. This level output function looks almost the same as the layer output function in Cogan,[1] but the heights and the respective variables are for the levels themselves vs. the upper boundary heights and integrated mean values of the layers. The layer output function now writes the midpoint heights of the layers instead of the heights of the layer upper boundaries, otherwise it's much the same as before. The changes for both the level and layer output functions were very small and consequently are not shown here. Computation of vector wind magnitude and density were performed on the spreadsheets using common formulas with the "direct" profile data as input.

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[1] Cogan J. A generalized method for vertical profiles of mean layer values of meteorological variables. Adelphi (MD): Army Research Laboratory (US); 2015. Report No.: ARL-TR-7434.

A-2 Pressure-Based Methods

The methods for pressure (P) levels and layers required greater changes to the respective programs though those changes were not large. The parameter file for user input contains pressure levels versus height levels. The output functions and files are nearly the same as those for the height-based output. Instead of output of height levels or height layer midpoints, the output files have pressure levels or pressure layer midpoints. Height or layer value heights are calculated as are the other meteorological variables. As noted in Section 2 the interpolation is in terms of the natural logarithm of P (ln[P]), not P. Consequently, the layer values of height shown are not strictly the values at the P midpoints, but rather the values at the ln(P) midpoints. A limited comparison using data from a few soundings from Dulles Airport, Virginia, and Idar-Oberstein, Germany, of P and ln(P) interpolation suggested the absolute values of the differences in computed values of height can be small (<1 m up to 4 m) for most layers, but for some it can rise to over 10 m and for a very few layers in the radiosonde-based profiles to over 20 m. At the highest levels in the radiosonde-based profiles (P < 20 hPa) where temperature increased with height, even larger differences appeared (maximum magnitude of 86 m [P vs. ln(P) interpolated heights] for the 10–15 hPa layer for Dulles Airport). The WRF-based profiles did not have a pressure less than 50 hPa, or in other words, it did not go above about 20 km. In the limited set of data examined the maximum absolute values of level or layer height difference was 7 m.

A-2.1 Msgvaluesprs Function

Here we present the main computation function (msgvaluesprs) where most of the substantive changes occurred. This function, in turn, uses 2 generalized functions, levelprs and layerprs, that perform linear interpolation and generation of integrated/weighted mean layer values respectively based on pressure (P) or some function of pressure such as ln(P) as was done here, where p = ln(P). The description of msgvaluesprs in pseudo code and text follows. The pseudo code uses some ‘C’ computer language syntax such as /* and */ to enclose comments, and a semicolon (;) to indicate the end of a line of code. The natural logarithm in ‘C’ is written as log vs. ln. The parameter ERROR (= -999) indicates missing or out of bounds data and is used to initialize most arrays.

```
Pass in the input data structure and the output data structure for the output layer values and the one
for the computed level values.
/* Note that the structures are structures of arrays that hold header information as well as the data.
Each level or layer is an element of an array that contains the values for that level or layer as
structure elements. Here p refers to ln(P).*/
 {
   /* message values = layer values, but may have different indices, mlevel = level values */
  Set the indices and the variable definitions.
```

```
  Set the temporary structures used within this function.
  /* For example, snd = (struct temporary *)malloc(sizeof(struct temporary));
  and similarly for leveltemp and layertemp. */

Initialize structures and temporary variables with the missing data/bad data indicator. /* Missing
or bad data indicated by the defined value ERROR = -999.0. */

/*Set parameters for level and layer values.  Here nht is number of pressure levels. */
  msg nht = mlevel nht - 1;  /* number of layer values one less than level values */
  size = snd nht;
  msize = mlevel nht;
  pmin = log(snd pressure at level[size-1]) - 0.0001;

/* Compute components from input sounding wind speed and direction. */

   start j at -1   /* Here j is used to count the number of levels with wind data.*/
   for i from 0 to < size incrementing by 1   /*Here i is the index for the input sounding data.*/
     {
      if(input wind speed at ith pressure not = ERROR and  input wind direction at ith pressure not =
ERROR)
        {
          add 1 to j;
          direction = -(input wind direction at pressure [i]) * PI/180 + 3* PI/2;
          snd u-component at pressure[i] = cos(direction) * input wind speed at pressure[i];
          snd v-component at pressure[i] = sin(direction) * input wind speed at pressure[i];
          snd p[j] = log(input pressure[i]);     /* Set to the ln of the input pressure. */
         }
     }
    wsize = j; /*wsize is the number of input levels with wind data. */

/* Compute temperature and virtual temperature. Temperature converted from C to K as needed in
calling main function. */

    /* Compute level values. */

/* Compute virtual temperature from input data. */
   for i from 0 to < size incrementing by 1
     {   /* tvfromtemp computes virtual temperature (Tv) from pressure (P), sensible temperature
(T), and relative humidity (H) using a standard method. Here pressure is the input pressure, not ln
pressure.*/
       virtual temperature at input data line[i] of input = tvfromtemp(temperature, pressure , relative
humidity) at data line[i]);
     }

/* Set up temporary variables for use in level and layer functions as needed.   Height is denoted as
Z. */
   start j at -1    /* Here j is used to count the number of levels with T, p, and H data. */
   for i from 0 to < size incrementing by 1    /*Here i is the index for the input sounding data.*/
     {
      if(height, T, and p at input data level[i] not = ERROR)
        {
         add 1 to j;
         snd T[i] = input sounding T at input data level[i];
         snd Tv[i] = input sounding Tv at input data level[i];
         snd Z[i] = input sounding Z at input data level[i];
```

```
          snd H[i] = input sounding H at input data level[i];
         /* Ln of pressure values for snd computed earlier.*/
        }
      }
   tsize = j; /*tsize is the number of input levels with T, Z, and H data. */

   for i from 0 to < msize incrementing by 1 /* Initialize temporary level and layer values of the ln
of pressure.*/
     {
       leveltemp p[i] = upper boundary level[i] p;
       layertemp p[i] = leveltemp p[i];
     }

   /*Compute level values for T, Tv, H, and Z where the level function for pressure is described in
this appendix.*/
/*In the function description the respective variables or arrays are pmin, msize, leveltemp p, input
value, leveltemp value, and input p. */

   levelprs(pmin, msize, leveltemp p array, snd T array, leveltemp T array, snd p array);
   levelprs(pmin, msize, leveltemp p array, snd Tv array, leveltemp Tv array, snd parray);
   levelprs(pmin, msize, leveltemp p array, snd H array, leveltemp H array, snd p array);
   levelprs(pmin, msize, leveltemp p array, snd Z array, leveltemp Z array, snd p array);

 /*Compute layer values for T, Tv, H, and Z where the layer function for pressure is described in
this appendix.*/
/*In the function description the respective variables or arrays are pmin, size, htsize, zh, value,
lev_value, lay_value, z.. */

   layerprs(pmin, tsize, msize, layertemp p array, snd T array, leveltemp T array, layertemp T
array, snd p array);
   layerprs(pmin, tsize, msize, layertemp p array, snd Tv array, leveltemp Tv array, layertemp Tv
array, snd p array);
   layerprs(pmin, tsize, msize, layertemp p array, snd H array, leveltemp H array, layertemp H
array, snd p array);
   layerprs(pmin, tsize, msize, layertemp p array, snd Z array, leveltemp Z array, layertemp Z
array, snd p array);

   /* Compute Wind Speed and Direction */

   /* Compute level values of wind components (u, v).  In this version p is the ln of pressure. */

   levelprs(pmin, msize, leveltemp p array, snd u array, leveltemp u array, snd p array);
   levelprs(pmin, msize, leveltemp p array, snd v array , leveltemp v array, snd p array);

   /* Compute level wind speed & direction from components (u, v). */

   for i from 0 to msize incrementing by 1
     {
       level[i] value of wind direction = (2* PI - atan2(leveltemp u[i], -leveltemp v[i])*180/ PI;
       if(level[i] direction > 360)
          subtract 360 from level[i] direction;

       level[i] value of wind speed = sqrt(leveltemp u[i] * leveltemp u[i] + leveltemp v[i] *
leveltemp v[i]);
     }
```

/* Compute layer values of components (u, v). */

layerprs(pmin, wsize, msize, layertemp p array, snd u array, leveltemp u array, layertemp u array, snd p array);
layerprs(pmin, wsize, msize, layertemp p array, snd v array, leveltemp v array, layertemp v array, snd p array);

/* Compute message layer wind speed & direction from components (u, v). Message values are the layer values in this function. */

surface message wind speed = input surface wind speed; /* i =0 at surface*/
surface message wind direction = input surface wind direction;
surface message u = computed surface u;
surface message v = computed surface v;

for i from 1 to < msize incrementing by 1
{ /* Here message level[i] value is the resultant layer[i] value. */
message level[i] u = layertemp u[i-1];
message level[i] v = layertemp v[i-1];

message level [i] wind direction = (2* PI - atan2(message level[i]u, -message level[i] v))*180/PI;
if (message level[i]direction > 360)
subtract 360 from message level[i] direction;

message level [i] wind speed = sqrt(message level[i] u * message level[i] u + message level[i] v * message level[i] v);
}

/* Load pressure values into the message structures. */

for i from 0 to < msize incrementing by 1
{
message level[i] p = level[i] p; /* "message level" refers to resultant layer. */
}

/* Load T, T_v, H, and Z values into level and message structures. */

for i = 0 to < msize incrementing by 1 /* level values */
{
level[i] T = leveltemp T[i];
level[i] T_v = leveltemp T_v[i];
level[i] H = leveltemp H[i];
level[i] Z = leveltemp Z[i];

}

message T at surface = input surface T; /* Message values for surface, where i =0. */
message T_v at surface = T_v from surface data;
message H at surface = input surface H;
message Z at surface = input surface Z;

for i from 1 to i < msize incrementing by 1
{
message level[i] T = layertemp T[i-1]; /* Message values above surface. */
message level[i] T_v = layertemp T_v[i-1];

```
      message level[i] H = layertemp H[i-1];
      message level[i] Z = layertemp Z[i-1];
    }

 /* Load in site information (date, time, lat, lon, etc.). */

   message site information = input site information;

 /*Free up temporary arrays in order to release memory. */

    free(snd);
    free(leveltemp);
    free(layertemp);

 return to calling function;
}
```

A-2.2 Alternate Version of msgvaluesprs Function

Section A-2.1 describes the primary version of msgvaluesprs. An alternate version computes height (zcomp) using the hypsometric formula. The hypsometric formula may be found in textbooks and the Glossary of Meteorology.[2] The main difference from the primary version of msgvaluesprs is the use of the procedure that uses the hypsometric formula instead of linear interpolation in terms of ln(P). Only the additional procedure is shown since the rest of the function is essentially the same except for the removal of statements for computation of heights as a function of ln(P). Here p is used to represent ln(P). As in the previous section 'C' type syntax is used in the pseudo code. The natural logarithm in 'C' is written as log vs. ln. The structure and variable names are the same as in the primary version in the preceding section. Note that snd(p) was set to snd(ln of pressure) prior to this excerpt from the alternate version of msgvaluesprs.

```
/* Start of height computation section.   P is pressure and p is ln(P).*/

surface level Z = snd surface Z;

   j=0;

   for(i=1; i<msize; i++)              /*Values for temporary sound structure set before level
calculations above. "mlevel" refers to pressure level values. */
     {
      while(snd p[j] > log(mlevel P at level[i])
        {
         j++;
        }

      if(snd p [j] == log(mlevel P at level[i]))  /*Sounding P = upper boundary P*/
```

[2] Glickman TS, managing editor. Glossary of meteorology. 2nd ed. Boston (MA): American Meteorological Society; 2000.

```
        {
          mlevel Z at level[i] = snd Z[j];
        }
      else
        {

          if(snd p[j-1] > log(mlevel P at level[i-1]) && j > 0)  /*Sounding P higher or height of
pressure level lower.*/
            {

              mlevel Z at level[i] = zcomp(mlevel Tv at level[i]., mlevel Tv at level[i-1],
                                  mlevel P at level[i-1], mlevel P at level[i], mlevel Z at level[i-1]);

            }
          else
            {
              mlevel Z at level[i] = zcomp(mlevel Tv at level[i], snd Tv[j-1],
                          exp(snd p[j-1]), mlevel P at level[i], snd Z[j-1]);     /* snd p is ln(input P)*/
            }

        }
    }
      /* End of computation of level pressures.*/

  /* Compute layer height values.  msg values = values for surface + values for layers.*/

  msg Z at surface  = mlevel Z at surface;     /* surface = level[0] */
  j=1;

  for(i=1;i<msize;i++)
    {

      while(snd p[j] > (log(mlevel P at level[i]) + log(mlevel P at  level[i-1]))*0.5)
        {
         j++;
        }

      if(snd p[j] == (log(mlevel P at level[i]) + log(mlevel P at level[i-1]))*0.5)
        {
         msg Z at level[i] = snd Z[j];
        }
      else
        {
         if(snd p[j-1] < (log(mlevel P at level[i-1]) + log(mlevel P at level[i-2]))*0.5)
           {
            Tv = msg Tv at level[i];
            Tv0 = mlevel Tv at level[i-1];
            P = (mlevel P at level[i] + mlevel P at level[i-1])*0.5;
            P0 = mlevel P at level[i-1];
            Z0 = mlevel Z at level[i-1];

            msg->level[i].hgt = zcomp(Tv, Tv0, P0, P, Z0);

           }
         else
           {
```

```
          Tv = msg Tv at level[i];
          Tv0 = snd Tv[j];
          P = (mlevel P at level[i] + mlevel P at level[i-1])*0.5;
          P0 = exp(snd p[j-1]);
          Z0 = snd Z[j-1];

          msg Z at level[i] = zcomp(Tv, Tv0, P0, P, Z0);

        }
      }
    }

  /* End of computation of layer pressure values.*/
```

A-2.3 Interpolation and Integrated Mean Functions

The levelprs and layerprs functions are close to the level and layer functions described in Cogan[1] that perform linear interpolation and computation of integrated mean layer values based on height. The main differences are the substitution of a pressure variable (p) for height, interpolation and computation of integrated mean from highest to lowest p values vs. lowest to highest height, and a procedure to check that p is greater or equal to some minimum value, pmin, vs. less than or equal to a maximum height, zmax. The variable p in these functions may represent P or ln(P), and similarly for pl. As in the previous section 'C' type syntax is used in the pseudo code.

A-2.3.1 Description of levelprs

Pass in the minimum value of p (pmin), the number of the user-defined pressure levels (prsize), the user-defined pressure levels (pl array), the input values of a variable (value array), and the input p data (p array). Pass out of the function the level values of the variable (lev_value array).

```
{
  set i=0 and j=0;   /* Starting at surface or level nearest surface.*/
  while(p[j] > pmin and pl[i] > pmin and i < prsize)
    {
      if(pl[i] less than or equal to p[0])  /* p[0] is the surface value (or for p level nearest the surface)
*/
        {
         if(pl[i] equals p[j])   /* Input pressure = defined pressure level.*/
           {
            lev_value[i] = value[j];
            add 1 to j;
           }
         else
           {
            if(p[j] less than pl[i])  /* use to go to previous input p (except for surface or level nearest
surface).*/
              {
                subtract 1 from j;
              }
            lev_value[i] = value[j] - (value[j] - value[j+1])*(p[j]-pl[i])/(p[j]-p[j+1]);
```

```
          /*Interpolate to obtain lev_value (value for given pressure level).*/
        }
      }

    while(pl[i+1] less than or equal to p[j+1] and p[j+1] greater than or equal to pmin and p[j] > -
999)   /*-999 indicates no data value*/
      {
        add 1 to j;
      }
    add 1 to i;  /* Go to next input p level. */
  }

  return;

} /* End of level function. */
```

A-2.3.2 Description of layerprs

Pass in the minimum value of p (pmin), the number of input data values of the variable (size), the number of the user-defined pressure levels (psize), the user-defined pressure levels (pl array), the input values of a variable (value array), the level values of the variable (lev_value array), and the input p data (p array). Pass out of the function the layer values of the variable (lay_value array).

```
{

 Set up the temporary arrays: tempval, tempp, and mean.

 i = 0;
 while(i is less than (psize-1) and pl[i+1] greater than or equal to pmin)   /* Find layer means.*/
   {
    add 1 to i;
    set ind = 0 and sum = 0;

    tempval[ind] = lev_value[i-1];    /* Lower (higher p) boundary values.*/
    tempp[ind] = pl[i-1];

    for (j starting at 0, to the highest value < size, incrementing by 1)
      {
       if(p[j] greater than pl[i] and p[j] less than pl[i-1])  /* Values within layer.*/
         {
          add 1 to ind;
          tempval[ind] = value[j];
          tempp[ind] = p[j];
         }
      }
    add 1 to ind;                             /* Upper (lower p) boundary level.*/
    tempval[ind] = lev_value[i];
    tempp[ind] = pl[i];

    for (j starting at 1, up to and including ind, incrementing by 1)  /* Sub-layer average.*/
      {
       mean[j-1] = (tempval[j] + tempval[j-1]) * 0.5;
      }

    for(j starting at 1, up to and including ind, incrementing by 1)  /* Proportional weighting of
each layer.*/
```

```
        {
         add (mean[j-1] * (tempp[j-1] - tempp[j])) to sum;
        }

      lay_value[i-1] equals sum /(pl[i-1] - pl[i]);    /* Mean layer value = sum/layer thickness.*/

    }    /* end of while loop.*/

   /* Free temporary arrays. ******/

   free(tempval);
   free(tempp);
   free(mean);

   return;

} /* End of layer function. */
```

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Appendix B. Charts of Mean Difference (MD), Mean Absolute Difference (MAD), Standard Deviation (SD), and Root Mean Square Difference (RMSD) for All Variables for Each of the 4 Methods

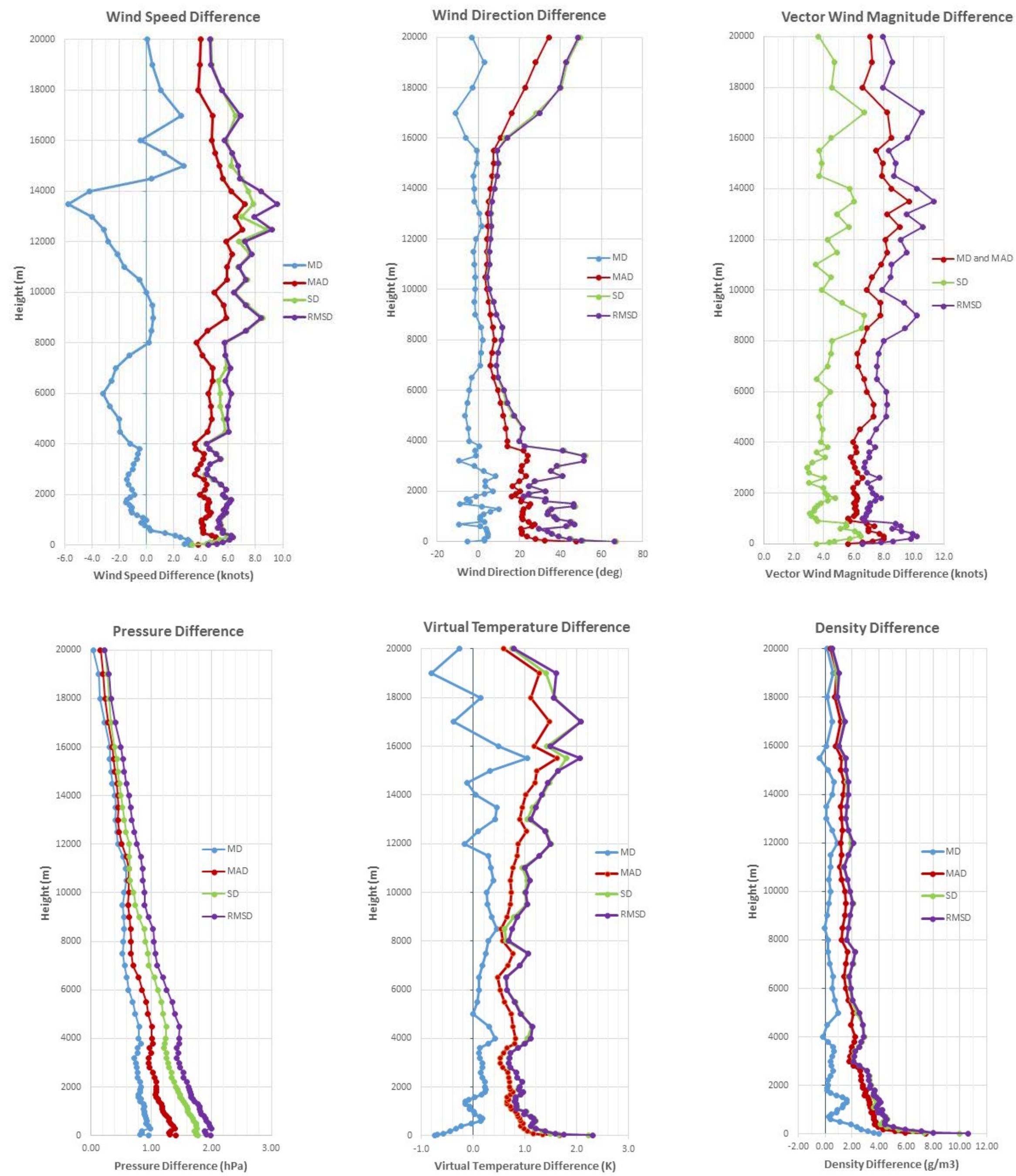


Fig. B-1 Statistical values (MD, MAD, SD, and RMSD) for the several variables for the user-defined height levels along with the number of samples for each height level

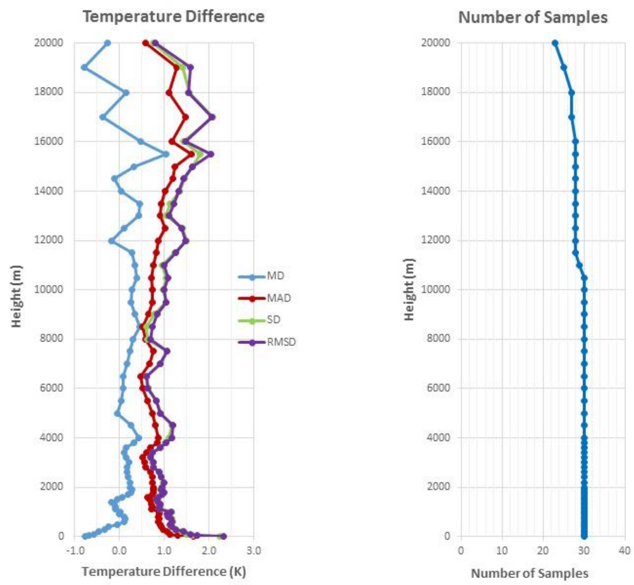


Fig. B-1 Statistical values (MD, MAD, SD, and RMSD) for the several variables for the user-defined height levels along with the number of samples for each height level (continued)

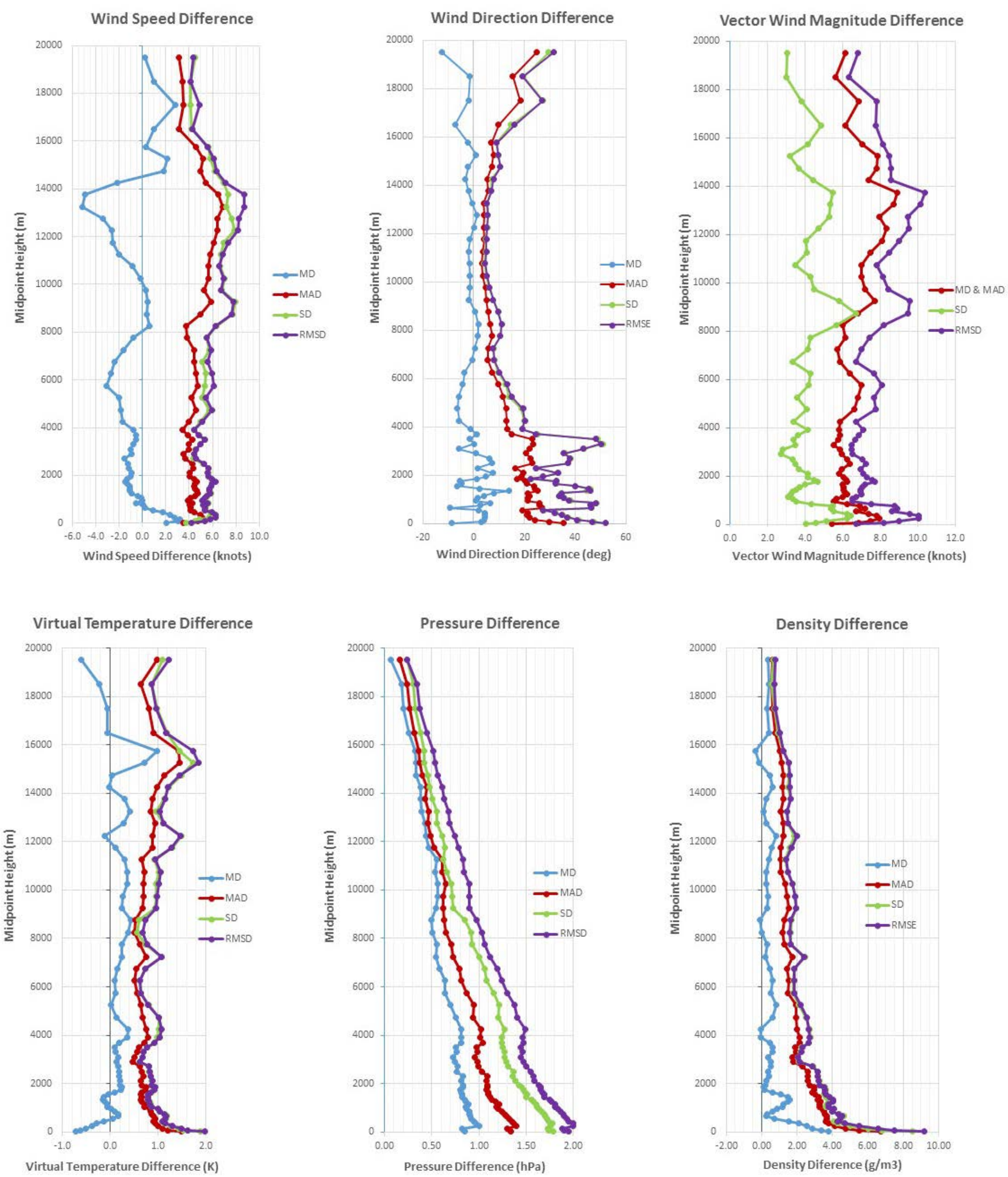


Fig. B-2 Statistical values (MD, MAD, SD, and RMSD) for the several variables for height layers defined by the user input height levels along with the number of samples for each height layer

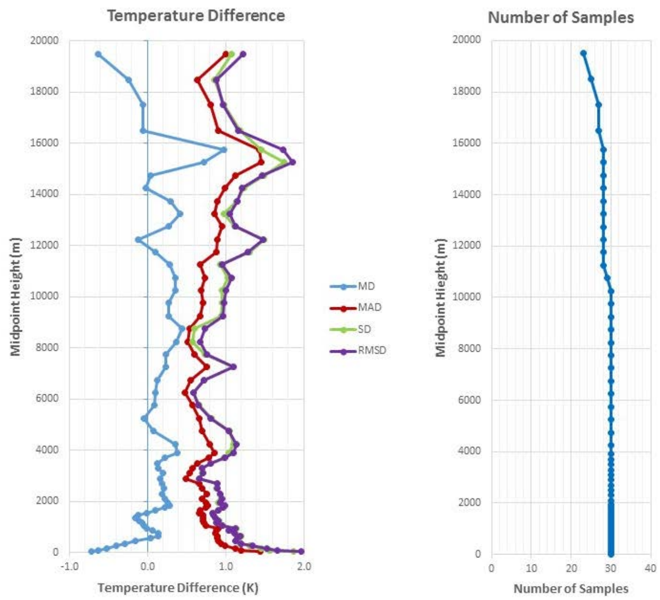


Fig. B-2 Statistical values (MD, MAD, SD, and RMSD) for the several variables for height layers defined by the user input height levels along with the number of samples for each height layer (continued)

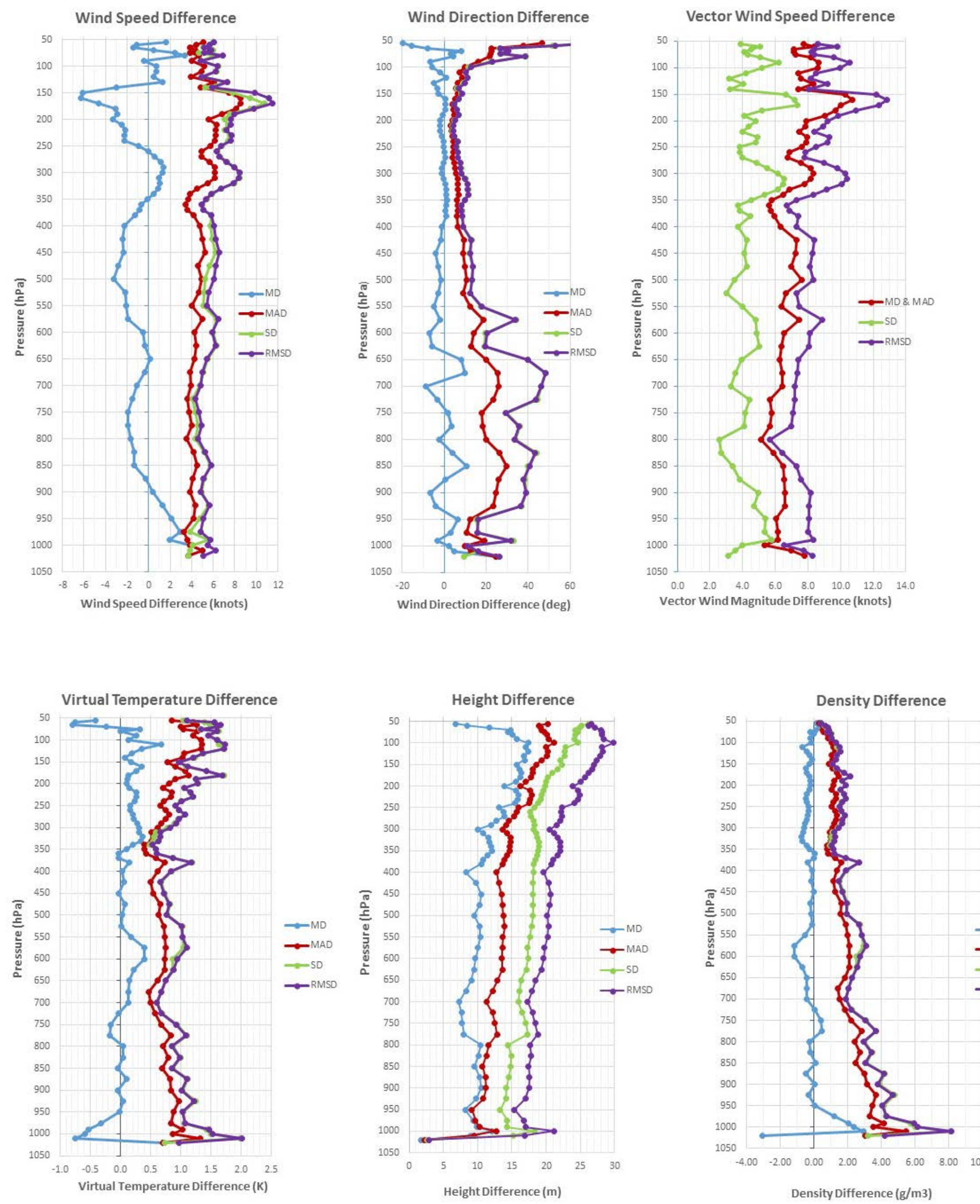


Fig. B-3 Statistical values (MD, MAD, SD, and RMSD) for the several variables for pressure levels defined by the user along with the number of samples for each level

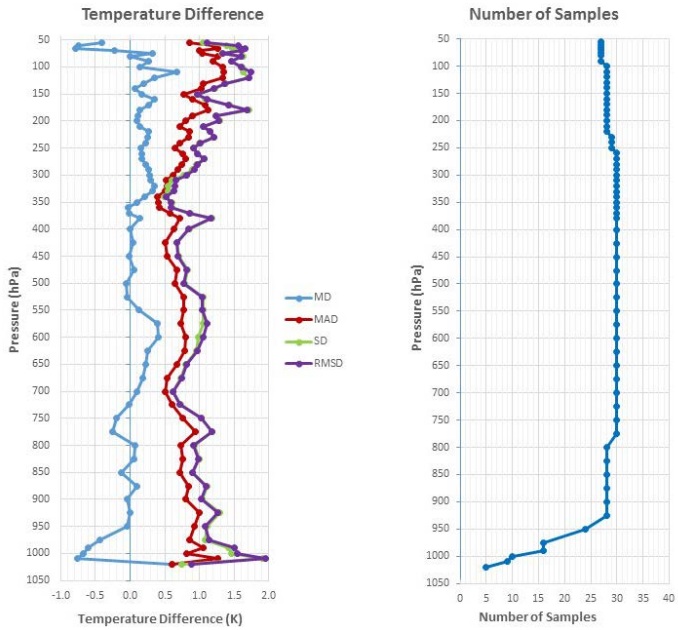


Fig. B-3 Statistical values (MD, MAD, SD, and RMSD) for the several variables for pressure levels defined by the user along with the number of samples for each level (continued)

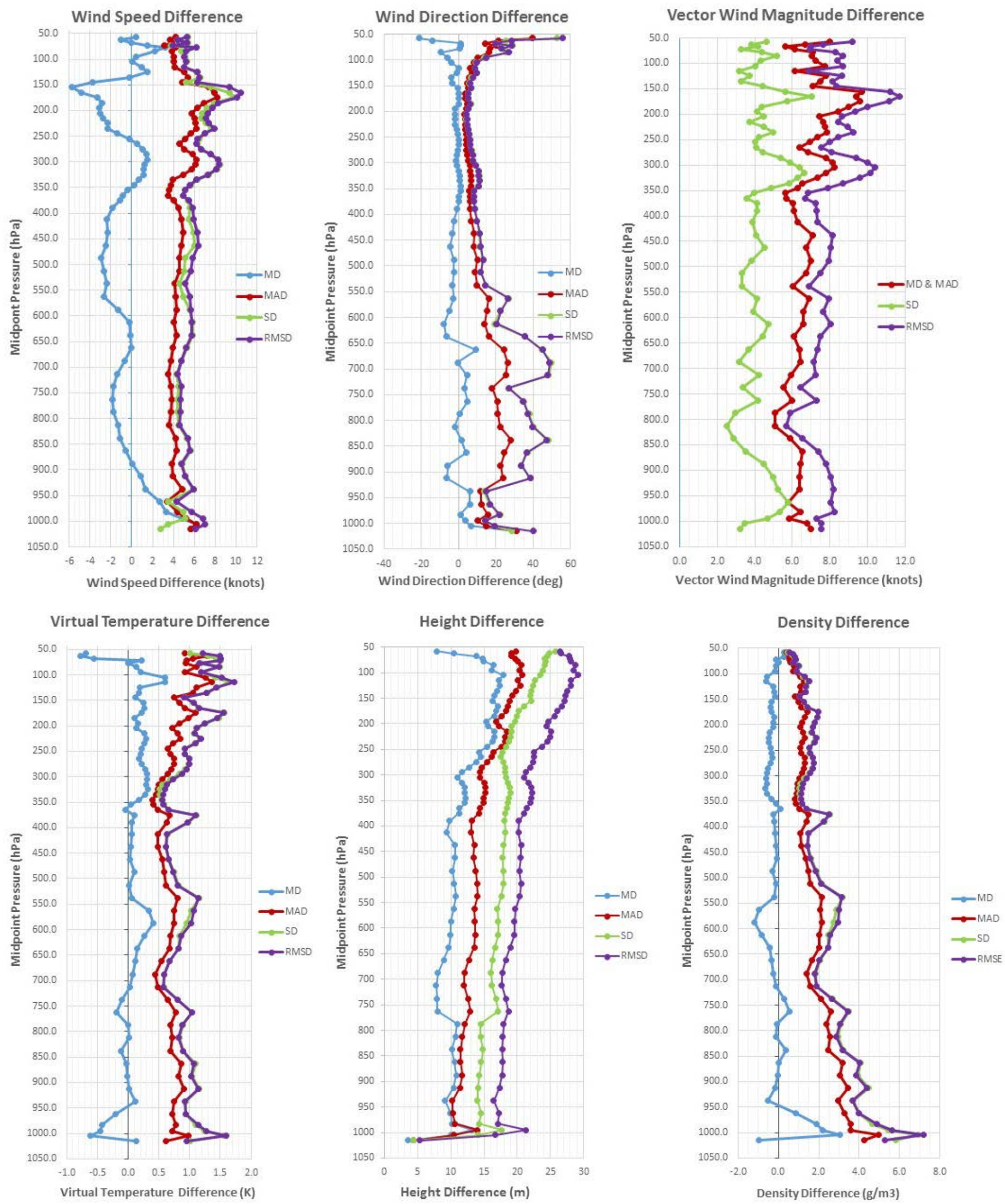
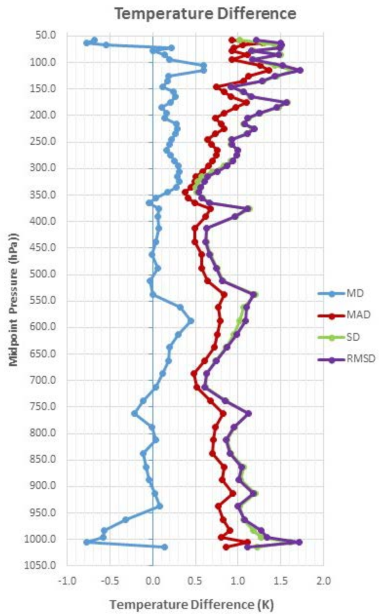


Fig. B-4 Statistical values (MD, MAD, SD, and RMSD) for the several variables for pressure layers defined by the user pressure levels along with the number of samples for each layer



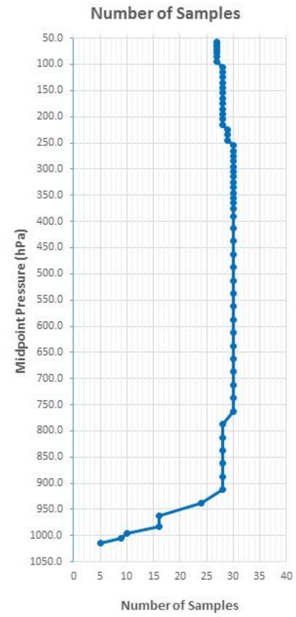


Fig. B-4 Statistical values (MD, MAD, SD, and RMSD) for the several variables for pressure layers defined by the user pressure levels along with the number of samples for each layer (continued)

List of Symbols, Abbreviations, and Acronyms

AGL	above ground level
ECMWF	European Center for Medium-Range Weather Forecasting
GFS	Global Forecast System
IMS	Ice Mapping System
JMA	Japan Meteorological Agency
M	mean value
MAD	mean absolute difference
MADIS	Meteorological Assimilation Data Ingest System
MAE	mean absolute error
METAR	Meteorological Aerodrome Report
MD	mean difference
MM5	Meteorological Model Fifth Generation
MSL	mean sea level
MYJ	Mellor-Yamada-Janjić scheme
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NCL	National Command Language
NOHRSC	National Operational Hydrologic Remote Sensing Center
NWP	numerical weather prediction
PWV	Precipitable Water Vapor
RAOB	radiosonde observation
RASS	radio acoustic sounding systems
RMSD	root mean square difference
RMSE	root mean square error
SAO	Surface Aviation Observation
SD	standard deviation

SNODAS	Snow Data Assimilation System
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting

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